

SOME TOPICS ON DOUBLE HEAVY MESONS: HEAVY QUARKONIA AND B_c MESON^a (Advances and outlooks)

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The most important advances achieved recently on the double heavy flavored mesons are reviewed. Some problems and outlooks on them are also outlined.

1 Introduction

The double heavy mesons, i.e. the heavy quarkonia ($c\bar{c}$), ($b\bar{b}$) and B_c meson as well as its excited states, are non-relativistic bound-state. Their static properties and most decays may be computed quite precisely by means of the potential model (PM) inspired in QCD and relevant theories as well, whereas their hadronic production was not understood so well, although the hadronic production of J/ψ is so important, not only for perturbative QCD (PQCD) theory itself but also for its applications, for instance, it is used as a probing tool to detect specific signature in nuclear processes such as that of quark gluon plasma (QGP) etc. Substantial progress on the hadronic production has been achieved in recent years. Last year, the discovery of the double heavy meson B_c opened up new challenges for studying the problems. Moreover, at tree level the B_c meson, being a ground state and in flavor non-singlet, decays by weak interaction only, and the branching ratios of the decays are sizable^b. Hence in addition to the mesons B and D , we will be able to study the weak decays of the heavy flavors b -quark and c -quark with the meson B_c .

2 Advances and Problems

Fresh progressions on the double heavy mesons are outlined below.

2.1 Advance on Fragmentation Functions of the Double Heavy Mesons

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^bOn the contrary, the ground states of heavy quarkonia (in flavor singlet) decay through strong and electromagnetic interactions mainly, that most of the branching ratios of the possible weak decays are so tiny beyond the capacity of the present experimental techniques, although the widths of the weak decays have the same order as those of the meson B_c .

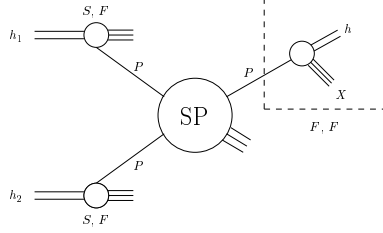


Figure 1: Factorization of an Inclusive Production for Hadron Collisions and Definition of Fragmentation Function (F.F.).

It is known that perturbative QCD (PQCD) works efficiently with its factorization theorem¹. Namely the ‘hard part’ involved a concerned process can be calculated perturbatively, but the ‘soft part’, e.g. structure functions (S.F.s) and fragmentation functions (F.F.s), being in non-perturbative nature, relating to the ‘color confinement’ and independent on the specific process, are just treated as ‘universal factors’. The factorization theorem and definition of a fragmentation function may be illustrated precisely by Fig.1 and (1) with an inclusive process.

$$d\sigma = \sum_{i,j,k} \int dx_1 \int dx_2 \int dx_3 F_{h_1}^i(x_1, \mu_F) \cdot F_{h_2}^j(x_2, \mu_F) \cdot d\sigma_{i,j \rightarrow k,x}(x_1, x_2, x_3, \mu_F) \cdot D_k^h(x_3, \mu_F), \quad (1)$$

where $F_{h_1}^i(x_1, \mu_F)$ and $F_{h_2}^j(x_2, \mu_F)$ are the S.F.s to depict the probabilities for finding a parton i in the hadron h_1 with momentum fraction x_1 and a parton j in the hadron h_2 with momentum fraction x_2 respectively; $d\sigma_{i,j \rightarrow k,x}(x_1, x_2, x_3, \mu_F)$ is the cross-section corresponding to the ‘hard subprocess’ (the SP-part in Fig.1); the factor $D_k^h(x_3, \mu_F)$ is just the F.F., which depicts a probability for the produced parton k to form a hadron h with a momentum fraction x_3 of the parton k . Here μ_F , denoting an energy scale, is noted where all the factors in the equation are matched, and sometimes it is omitted for simplification if there is no confusion. The fragmentation functions, being considered independent of the specific process, contain nonperturbative effects, that generally they are considered not to be calculable, but may be determined by measurement(s). Thus F.F.s are important blocks for PQCD calculations.

Recently, an advance is to be realized that the fragmentation functions (F.F.s) for double heavy mesons can be factorized further, and some of them,

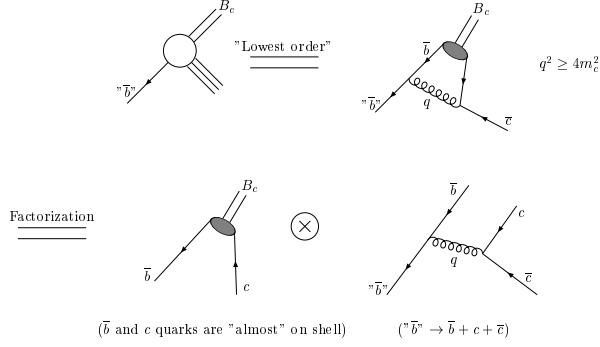


Figure 2: The Further Factorization for a Fragmentation Function of the Double Heavy Meson B_c (an example).

for the so-called color singlet ones, even can be calculated out precisely without any free parameter^{2,3,4}. Taking a F.F. of the meson B_c as an example, let me with Fig.2 to illustrate the ‘further factorization’. Note here that the virtual gluon which creates a pair of c, \bar{c} as depicted in Fig.2 is crucial for the further factorization. It is because that the gluon carries a time-like momentum, and always has $q^2 \geq 4m_c^2 \gg \Lambda_{QCD}^2$, so that it is guaranteed the factor involving the gluon being perturbative. Namely, due to the very virtual gluon, the further factorization makes sense, and we may calculate out the perturbative part of the F.F. precisely. In the cases, when the ‘residual’ factor of the further factorization is in color singlet, although being non-perturbative, the residual factor may be directly related to the wave functions of the potential model directly, i.e. it can be calculated precisely without any free parameter. Therefore a fragmentation function for a double heavy meson can be calculated out either totally if the residual factor is in color-singlet which may be related to the wave function of potential model directly, or partly i.e. only the virtual gluon part may be calculated out and the residual factor, as a factor to be determined, is left in the ‘final result’ if the residual factor is in color non-singlet.

To take an example and to see the general features, a typical fragmentation function, calculated out by the method first², has the behavior:

$$D_b^{B_c}(z, m_{B_c}) \propto \alpha_s^2(m_{B_c}^2) |\psi(0)|^2 \frac{z(1-z)^2}{(a_2 z - 1)^6} \cdot \{ [2a_1 z - 3(a_2 - a_1)(1 - a_2 z) \cdot (2 - z)] (1 - a_2 z) z + 6(1 + a_1 z)^2 (1 - a_2 z) - 8a_1 a_2 z^2 (1 - z) \}, \quad (2)$$

where $|\psi(0)|$ is wave function at original of the B_c meson; $\alpha_s^2(m_{B_c}^2)$ is the QCD coupling constant at $m_{B_c}^2$; and $a_1 = m_c/m_{B_c}$, $a_2 = m_b/m_{B_c}$.

2.2 Advances: ‘Puzzle’ and Solution for Charmonium Production

Thanks to the realization about the further factorization for the fragmentation functions of double heavy mesons, various fragmentation functions not only for the mesons B_c, B_c^*, \dots but also for the heavy quarkonia ($c\bar{c}$) and ($b\bar{b}$) have been computed. For the hadronic charmonium production, on one hand, the experimental advance is the data have been accumulated for many years, and new achievements in experimental techniques have made it possible to separate the prompt production events of charmonia $J/\psi, \psi', \chi_c, \dots$ from those events as decay-products of the produced B mesons in hadron collisions successfully⁵; on the other hand, the theoretical advance on the fragmentation function computation for those of color singlet: the fragmentation functions have been calculated out precisely by means of the wave functions obtained by potential model (all the parameters appearing in the calculation having been determined well elsewhere), therefore thorough comparisons between theoretical predictions and experimental data become possible and interesting. Indeed the comparisons were carried through just after the advances being achieved.

An important result of the comparison, the so-called ‘ ψ' surplus puzzle’, rose and confirmed. Namely, of the prompt production of J/ψ and ψ' in hadron collisions, the experimental data are greater than theoretical prediction by one to two orders in magnitude and the behavior of the P_T (the transverse momentum of the produced mesons) dependence for experimental data and theoretical prediction is also inconsistent, if only the color singlet F.F. is taken into account. We would like to note here that the advance on the computation of the fragmentation functions for double heavy mesons is crucial to recognize the puzzle, namely, without the advance, the fragmentation functions would be able only to be determined by experimental measurement in whole, that the deviation (the puzzle) would be ‘absorbed’ into the determination to disappear. Based on analysis of the puzzle, Braaten and Fleming proposed the so-called color octet mechanism first⁶. Following them, many groups applied the proposition to various processes widely, including to nuclear processes⁷ to explore the consequences of the new mechanism. Since in the proposition a new undetermined parameter, the so-called color-octet matrix element (C.O.M.E.) which is of non-perturbative feature and uncalculable, is introduced, hence the solution of the ‘surplus puzzle’ essentially is to determine the matrix element first and then to test it with the other available data. Only with constant matrix elements determined by fitting data to obtain correct behavior of the P_T dependence of the production has ‘absolute meaning’ for the proposition. The

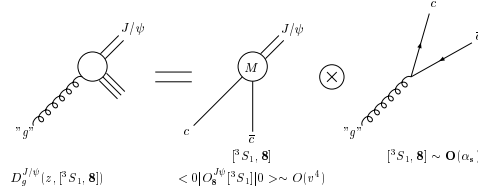


Figure 3: 1. The Color Octet Component $c\bar{c}([{}^3S_1, \mathbf{8}])$.

reference⁶ paid attention to the P_T dependence of the production on large P_T mainly, but afterwards others tried to have a complete determination of the matrix elements for various color octet components by fitting whole behavior of P_T -dependence (at large and small P_T) of the hadronic production^{8,9,10}.

Taking the charmonium meson J/ψ as an example let me outline the key point of the proposition. A physical state of J/ψ , in general, should be expressed in Fock space:

$$|J/\psi\rangle = O(v^0)|c\bar{c}([{}^3S_1\mathbf{1}])\rangle + O(v)|c\bar{c}([{}^3P_J\mathbf{8}])g\rangle + O(v^2)|c\bar{c}([{}^1S_0\mathbf{8}])g\rangle + O(v^2)|c\bar{c}([{}^3S_1\mathbf{8}])gg\rangle + O(v^2)|c\bar{c}([{}^3D_J\mathbf{1}, \mathbf{8}])gg\rangle + \dots, \quad (3)$$

where v is 4-velocity of the constituents of the meson J/ψ , and, due to J/ψ being heavy nonrelativistic bound state, $v^2 \simeq 0.3$ is acceptable; g indicates a ‘valance’ gluon; and the factor $O(v^i)$ at the front of each term indicates the relative order of the term which is obtained based on the counting rules of the effective theory: nonrelativistic QCD (NRQCD)¹¹. It is known that J/ψ is a ‘flavor singlet’ meson, thus it has the same quantum number in flavor as a gluon, especially, its component in the Fock space expansion ($c\bar{c}([{}^3S_1\mathbf{8}])$) has the same quantum numbers of a gluon. As a result of the fact, J/ψ production in hadron collisions will present a quite complicated feature i.e. in a sense it may be considered as a kind of ‘mixing’ between the components of higher Fock space with a gluon. The fragmentation function of a gluon to J/ψ , $D_g^{J/\psi}(z, \mu_F = 2m_c)$, may be used as an example to illustrate how to solve the surplus by the ‘mixing’. For charmonium, in general, we have $v^2 \simeq 0.3$ and $\alpha_s(4m_c^2) \simeq 0.2 \sim 0.3$, therefore, there are components for the fragmentation function, which have contribution in the same order of magnitude, according to naive NRQCD power-counting rule, are listed below:

1. The color octet component ($c\bar{c}([{}^3S_1, \mathbf{8}])$) (**Figure 3:1**):

$$D_g^{J/\psi}(z, [{}^3S_1, \mathbf{8}]) = \langle O_8^{J/\psi}[{}^3S_1, \mathbf{8}] \rangle \times \Gamma_{g \rightarrow (c\bar{c}([{}^3S_1, \mathbf{8}]))}(z). \quad (4)$$

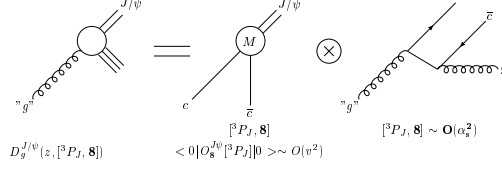


Figure 3: 2. The Color Octet Component $c\bar{c}([^3P_J, \mathbf{8}])$.

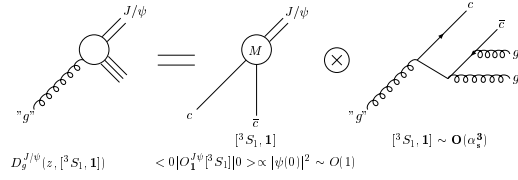


Figure 3: 3. The Color Singlet Component $c\bar{c}([^3S_1, \mathbf{1}])$.

2. The color octet component ($c\bar{c}[^3P_J, \mathbf{8}]$) and ($c\bar{c}[^1S_0, \mathbf{8}]$) (**Figure 3:2**):

$$D_g^{J/\psi}(z, [^3P_J, \mathbf{8}]) = \langle O_8^{J/\psi} [^3P_J, \mathbf{8}] \rangle \times \Gamma_{g \rightarrow (c\bar{c}[^3P_J, \mathbf{8}])g}(z), \quad (5)$$

$$D_g^{J/\psi}(z, [^1S_0, \mathbf{8}]) = \langle O_8^{J/\psi} [^1S_0, \mathbf{8}] \rangle \times \Gamma_{g \rightarrow (c\bar{c}[^1S_0, \mathbf{8}])g}(z). \quad (6)$$

Note that for shortening in Fig.3:2, only ($c\bar{c}[^3P_J, \mathbf{8}]$) is presented, but ($c\bar{c}[^1S_0, \mathbf{8}]$), being similar, is not.

3. The color singlet component ($c\bar{c}[^3S_1, \mathbf{1}]$) (**Figure 3:3**):

$$D_g^{J/\psi}(z, [^3S_1, \mathbf{1}]) = \langle O_8^{J/\psi} [^3S_1, \mathbf{1}] \rangle \times \Gamma_{g \rightarrow c\bar{c}([^3S_1, \mathbf{1}])gg}(z). \quad (7)$$

Based on power counting and as indicated in Figs.3:1-3 no matter the component in the color-octet or in color-singlet, each may contribute to the F.F. in the same order of magnitude, that we should treat them ‘equally’.

2.3 The Problem(s) of the Proposition

Indeed the color octet proposition is very attracting because it is on NRQCD formalism and can solve the puzzle by choosing the color octet matrix elements (C.O.M.E.) properly. Whereas the C.O.M.E. cannot be calculated due to its nonperturbative nature (there is a long way to go also for Lattice QCD), and furthermore, exactly to say, the proposition has not been well-proved yet.

The proof of the proposition should be either to show the determination of C.O.M.E. is independent of the chosen processes, or one and more of its characteristic signatures are observed in experiments. Whereas the status of this kind of proof now is that a lot of suggestions on the characteristic signatures are proposed but no one has been observed in experiments definitely^c; for the determination of C.O.M.E., the situation is neither definite: An example for the situation of the determination of C.O.M.E.^{8,9,10} is shown in Table 1.

Table 1: Color-octet matrix element linear combinations.

Matrix elements	$\langle O_{\mathbf{8}}^{j/\psi}(^3S_1) \rangle (in\ GeV^3)$	$\frac{\langle O_{\mathbf{8}}^{j/\psi}(^3P_0) \rangle}{M_c^2} + \frac{\langle O_{\mathbf{8}}^{j/\psi}(^1S_0) \rangle}{3} (in\ GeV^3)$
NRQCD scaling order	$M_c^3 v^{\prime}$	$M_c^3 v^{\prime}$
Cho et al ⁸	$(6.6 \pm 2.1) \times 10^{-3}$	$(2.2 \pm 0.5) \times 10^{-2}$
Beneke et al ⁹	$(1.06 \pm 0.14) \times 10^{-2}$	\sim
Sridhar et al ¹⁰	$(1.26 \pm 0.33) \times 10^{-2}$	$(3.14 \pm 0.58) \times 10^{-2}$

Note: those of Beneke et al⁹ are taken only for $\langle k_T \rangle = 0$. The values in the table are obtained only based on the data of Tevatron, and those from the lepton(photon)-production and fixed target ones are not involved because of more complications. The values of C.O.M.E. in the table are quite ‘scattering’ that I think it is hard to draw any conclusion about proving the proposition.

2.4 B_c Mesons: Theoretical Predictions and Experimental Discovery

The meson B_c is the unique one of the possible double heavy mesons in flavor non-singlet. Being a double heavy meson, its properties may be estimated well with the potential model and recent advances.

Based on the potential model, the estimated mass of the meson is not very large in the region $6.2 - 6.4\ GeV$ ¹⁴.

The lifetime of the meson may be estimated by the spectator mechanism and the ‘CKM favor’ annihilation of the two components c -quark and \bar{b} -quark into c, \bar{s} -quarks and τ^+, ν -leptons (there is helicity suppression that those of annihilating into the other possible quark pairs and lepton pairs besides into c, \bar{s} -quarks and τ^+, ν -leptons may be ignored safely). The two spectator terms are the same as those for B meson and for D meson respectively, thus they may relate to the widths of the B meson and the D meson i.e. we may estimate the contribution of the two spectator terms to the width of the meson B_c from the experimental measurements on the lifetimes of the mesons B and $D^0(D_s)$ respectively, and the annihilation contribution may be computed easily with

^cOne clean signature of the proposition was proposed in reference¹², but considering to the backgrounds pointed out in Ref.¹³ and experimental errors, one cannot conclude a clean signature has been observed. The other suggestions are worse than the mentioned one.

the wave function (decay constant) of the meson B_c . The estimated lifetime of the meson B_c is about 0.4×10^{-12} s^{15,16,17}.

Since the mass of the meson is not very great, the production of the meson had not been expected so ‘difficult’ as realized now: Of the present facilities, for experimental detecting only at Tevatron, enough number of B_c mesons can be produced; in e^+e^- colliders only at Z resonance LEP-I marginal number of the mesons can be produced; of the planned facilities, at such a high energy hadronic collider LHC, numerous mesons will be able to be produced^{2,18,19}. Quantitative values depend on the cuts of transverse momentum P_T and rapidity y quite sensitively. Comparative study on the production calculated by full α^4 calculation of PQCD and by simplified ‘fragmentation mechanism’ showed that due to convolution in the total cross section the differences of the two approaches were smoothed out accidentally¹⁹.

As for the weak decays of the meson B_c , there are many decay channels that contain a charmonium in the final state. Especially, when the charmonium in final state is J/ψ , the decays may be used as a characteristic signature for identifying the produced meson B_c because of the detecting advantages of J/ψ : narrow width and sizable branching ratio to a lepton pair $l\bar{l}$ etc. To compute all the decays, there are many ways^{15,17,20}, but let me pick up one, the so-called generalized instantaneous approximation approach^{15,21} to illustrate a little more in detail. The non-relativistic wave functions of the mesons B_c and J/ψ may be calculated out in potential model framework, but there may be a great (relativistic) momentum recoil ($m_{B_c} \simeq 6.3$ GeV, $m_{J/\psi} \simeq 3.0$ GeV, i.e. the produced J/ψ may move relativistically in C.M.S. of B_c). The so-called generalized instantaneous approximation approach is to start with a relativistic formulation, which is based on Bathe-Salpeter (B.S.) equation for the double heavy mesons and Mandelstam method for the transition matrix elements²², to write down the relevant decay matrix element and then to make an ‘instantaneous approximation’ on the whole matrix element in a similar way as the ‘original instantaneous approximation’ on B.S. equation done by Salpeter first. Finally as the result of the approach, the matrix element is related to certain operators sandwiched by the nonrelativistic wave functions (the instantaneous ‘limit’ of the B.S. equations) properly. Let me quote the semileptonic decay widths estimated by the approach and some other approaches in Table 2.

Table 2: Exclusive semileptonic decay width for various modes

Mode	Reference ¹⁵ (in 10^{-6} eV)	Reference ¹⁷ (in 10^{-6} eV)
$B_c \rightarrow \eta_c + l^+ \nu_l$	14.2	10.6
$B_c \rightarrow J/\psi + l^+ \nu_l$	34.4	38.5

The meson B_c was searched for at LEP-I, but not seen²³. It was just

discovered by CDF Collaboration last year²⁴. Now no one doubts the discovery, although CDF Collaboration was based on about 20 events of the cascade decays $B_c \rightarrow J/\psi + l\nu$, $J/\psi \rightarrow \mu^+\mu^-$ and reported three measurements with quite large error bars only. The three are its mass, lifetime and a combination of the production cross section and the decay branching ratio of the meson.

In summary for comparison, the CDF results of the three measurements:

$$m_{B_c} = 6.40 \pm 0.39 \pm 0.13, \quad (8)$$

$$\tau_{B_c} = 0.46_{-0.16}^{+0.18}(\text{stat.}) \pm 0.03(\text{syst.}) \times 10^{-12} \text{s}, \quad (9)$$

and a combination of the production cross-section and decay branching ratio ‘normalized’ by those of B meson’s:

$$\begin{aligned} R &\equiv \frac{\sigma \cdot Br(B_c \rightarrow J/\psi + l^+ + \dots)}{\sigma Br(B^+ \rightarrow J/\psi + K^+)} \\ &= 0.132_{-0.027}^{+0.041}(\text{stat.}) \pm 0.031(\text{syst.})_{-0.020}^{+0.032}(\text{lifetime}). \end{aligned} \quad (10)$$

The ratio R , the mass m_{B_c} and the lifetime τ_{B_c} all are in the region of theoretical predictions²⁴.

Since the rest decay channels have not been observed yet, thus to shorten the paper, I would not list them here, but just to mention the most interesting one $B_c \rightarrow J/\psi\pi$: roughly speaking, the width is small: just about one tenth of $B_c \rightarrow J/\psi + l^+\nu_l$, so we may expect it will be observed soon in RUN-II of Tevatron. Since each particle of the final state in the decay can be well-detected, so it is the best channel to measure the mass of the meson B_c .

3 Outlooks

The advances and problem(s) on double heavy mesons have been outlined. It certainly is breakthrough progress, that of a physical state not only the color-singlet components but also the color-octet components in Fock space Eq.(3) may play very substantial roles, although it still needs to be further proved. The progress should have wide consequences to be explored. Reviewing the advances on the topics, many subjects are just at beginning i.e. there are many ‘things’ needed to be study further.

RUN-II of Tevatron will present its the first results within two or three years. In the next run: RUN-II, the total statistics will be raised by one or more order of magnitude, and the detectors will also be improved greatly so the systematic errors will be suppressed and the ratio of the signal to background will be raised much etc. In addition, considering to LHC to be built, we believe that in the very near future on the color-octet mechanisms of heavy quarkonium production, systematic studies of the meson B_c and much deeper understanding must be achieved. Namely motivated by the foreseeing experimental

achievements, including searching for the signatures of the color-octet proposition, the C.O.M.E. measurements, accumulation of more B_c events and more accurate theoretical calculations on B_c meson etc must gain great progress soon.

One specific point which I would like to address here is that a comparative study of the hadronic production of the heavy quarkonia and the meson B_c is very helpful to clarify up the situation of the color-octet proposition. If the proposition is a correct solution for the original ‘surplus’ puzzle then it is necessary that for the production of B_c meson there is no the ‘surplus’ at all, because the meson B_c is in flavor non-singlet that the color-singlet component contribution in the production is always to play a dominant role, on contrary, a heavy quarkonium in flavor singlet, as indicated by Figs.3:1-3, can gain the ‘surplus’ by the ‘mixing’ with a gluon i.e. a color-octet component can be produced in a lower order of PQCD than the color-singlet one although the former has a smaller possibility to form the hadron finally (C.O.M.E. is smaller).

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